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CONTRIBUTIONS FROM THE JEFFERSON PHYSICAL LABORATORY, HARVARD UNIVERSITY.

THE MAGNETIC PERMEABILITIES AT LOW EXCITATIONS OF TWO KINDS OF VERY PURE SOFT IRON.

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More than a year ago, I had occasion to study the magnetic properties under very high excitations of a piece of Norway iron[1] (P), which proved when analyzed to be extraordinarily pure. The tests made in the Chemical Laboratory of Harvard University by Mr. E. R. Riegel, for nickel, cobalt, tungsten, and even manganese, as well as for the metals of Groups IV and V, were all negative. There was less than 0.03 per cent of carbon, less than 0.047 per cent of phosphorus, less than 0.03 per cent of silicon, and less than 0.003 per cent of sulphur. A slender rod of this remarkable iron, of which we had originally a round bar five centimeters in diameter and thirty-four centimeters long, had, when annealed, an extremely high permeability under excitations above 200, but, because of the local reluctance at the joints, it did not prove easy to determine the permeability of this rod in a yoke at low excitations. The metal showed to the eye a fibrous structure with striae parallel to the length of the bar, as if minute quantities of scale had been included in the bar in the rolling; and it seemed likely that the specific reluctance to magnetization across the grain of the iron, would be greater than to magnetization parallel to the grain. Under these circumstances it was probable that the permeability of a ring, so cut from the metal that its axis should be parallel to the grain, would appear low. It happened, however, that I had two such rings, but that there was not enough of the iron left to make rings with axes perpendicular to the grain, and I was forced to get what information I could from them, though it soon became evident that for excitations above five gausses the permeability fell below what commercial Norway iron should show.

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[1] American Journal of Science, **28**, July, 1909.

This paper gives the results of some tests made at low excitations, which are interesting because of the great susceptibility which the rings showed in fields less than two gausses, and compares the magnetic behavior of this metal with that of a ring of the so-called "American Ingot Iron," which I obtained through the kindness of Dr. P. W. Bridgman. This well-known iron, which was made by the American Rolling Mill Company of Middletown, Ohio, seems to be perfectly homogeneous, and, according to the makers, contains less than 0.03 per cent of impurities all told.

All the rings were very accurately made by Mr. G. W. Thompson, the mechanician of the Jefferson Laboratory. The external diameters of the Norway iron rings were 5.000 cm. and 4.996 cm. respectively; their thicknesses were 0.250 cm. and 0.254 cm., and their breadths were 1.2204 cm. and 1.210 cm. The measurements were made with the help of Zeiss Comparator No. 3196 and a set of auxiliary gauges. After each ring had been measured, a coil of very fine double-silk-covered copper wire was wound on the metal in a single layer and then baked in shellac. Over this was wound, usually in two layers, the exciting coil of well-insulated wire nearly one millimeter in diameter. The ballistic galvanometers were of the moving coil type, and had periods amply long enough [2] for the work. The fine coil on the ring was always in simple circuit with the galvanometer and the secondary coil of a standard of self inductance tested by the Bureau of Standards.

The maximum value of the permeability (5480) which I obtained for the first ring tested seemed so high that at first I suspected that there was some error in the determination, so I changed the galvanometer, and then took off the coils and wound on new ones with different numbers of turns; but when the result was unchanged and the second ring gave values for the ordinates of the HB diagram which were practically indistinguishable from those obtained from the first ring, there seemed to be no doubt that the work had been accurately done. The two rings lay side by side in the original bar, and both must have had nearly the same discontinuities. Table I, founded upon several hundred separate determinations, gives values of the permeability of the metal obtained from 35 different excitations of the first ring and 25 of the second. A ring of very pure annealed iron from the Armstrong Works at Elswick gave in the hands of Wilson the same maximum value of the permeability as the rings just mentioned; but apart from the reports of some tests upon thin pieces of electrolytically deposited iron,

[2] Peirce, These Proceedings, **44**, 1909 (283).

I have found no other records of permeabilities so high as this.[3] For excitations above six gausses, however, the rings were distinctly less permeable than good iron should be, and this anomalous behavior is perhaps due to discontinuities across the lines of magnetization.

TABLE I.

Annealed Ring of Norway Iron (P), Axis parallel to the Axis of the Original Bar. Measurements made by the Method of Ascending Reversals.

H.	*B.*	*B/H.*	*I.*	*H.*	*B.*	*B/H.*	*I.*
0.05	22	440	1.7	1.70	9040	5320	719
0.10	54	540	4.3	1.80	9340	5190	743
0.15	92	613	7.3	1.90	9640	5070	767
0.20	145	725	11.3	2.00	9870	4935	785
0.25	205	820	16	2.20	10300	4680	820
0.30	280	933	22	2.40	10690	4450	851
0.35	390	1114	31	2.60	11010	4230	876
0.40	495	1238	39	2.80	11310	4040	900
0.45	620	1377	49	3.00	11560	3850	920
0.50	790	1580	63	3.50	12010	3430	956
0.55	990	1800	79	4.00	12310	3080	980
0.60	1260	2100	100	4.50	12550	2790	991
0.65	1585	2440	126	5.00	12760	2550	1016
0.70	1980	2830	158	6.00	13060	2180	1039
0.75	2405	3205	191	7.00	13300	1900	1058
0.80	2850	3560	227	8.00	13510	1690	1075
0.85	3310	3890	263	9.00	13700	1520	1090
0.90	3780	4200	301	10.00	13870	1387	1103
0.95	4255	4480	339	20.00	14950	748	1188
1.00	4730	4730	376	30.00	15520	517	1233
1.10	5620	5110	499	40.00	15850	396	1258
1.20	6380	5320	508	50.00	16080	322	1276
1.30	7070	5440	563	60.00	16300	271	1292
1.40	7670	5480	610	70.00	16510	236	1308
1.50	8200	5470	653	80.00	16700	209	1322
1.60	8640	5400	687				

[3] Stoletow, Ann. d. Physik, **146**, 1872 (439); Riecke, Ann. d. Physik, **149**, 1873; Rowland, Phil. Mag., **46**, 1873 (140); Roessler, Inaugural Diss., Zürich, 1892; Holz, Ann. d. Physik, **8**, 1876 (353); Ewing, Magnetic Induction in Iron and Other Metals; Bauer, Ann. d. Physik, **11**, 1880 (349); G. vom Hofe, Ann. d. Physik, **37**, 1889 (482); Lehmann, Ann. d. Physik, **48**, 1893 (406); Benedicks, Ann. d. Physik, **6**, 1901; Lydall and Pocklington, Proc. Roy. Soc., **52**, 1892;

A well annealed isthmus of this iron cut lengthwise of the bar gave for *I*, under excitations as high as 18000 gausses, a final value of 1795, and an unannealed rod tested in a yoke gave 1730. These remarkable values point to a much higher permeability at medium excitations than the rings just mentioned show.

TABLE II.

Ring of Annealed "American Ingot Iron." Measurements made by the Method of Ascending Reversals.

H.	*B.*	*B/H.*	*I.*	*H.*	*B.*	*B/H.*	*I.*
0.1	35	175	2.8	4.0	11900	2975	947
0.3	106	530	8.4	4.5	12450	2777	991
0.2	198	660	15.7	5.0	12850	2570	1022
0 4	324	810	26	5.5	13200	2400	1050
0.5	482	964	38	6.0	13500	2250	1074
0.6	688	1147	55	6.5	13780	2120	1096
0.7	990	1414	79	7.0	13960	1994	1111
0.8	1325	1656	105	7.5	14180	1891	1128
0.9	1720	1911	137	8.0	14350	1794	1142
1.0	2320	2320	185	8.5	14480	1763	1152
1.5	5150	3433	410	9.0	14600	1622	1162
2.0	7340	3670	584	9.5	14720	1550	1171
2.5	9050	3620	720	10.0	14830	1483	1180
3.0	10220	3406	813	20.0	15850	792	1261
3.5	11150	3186	887				

Table IV shows corresponding values of *H* and *B* for a ring of annealed "American Ingot Iron" cut out by Mr. Thompson from a large plate of the metal. The outside diameter of the ring was 5.012 cm., its thickness was 0.283 cm., and its breadth about 2.116 cm. There were 112 turns in the testing coil and 74 turns in the exciting coil.

Table III gives for comparison the results of the determinations of the permeabilities of a number of different specimens of soft iron by different observers. Some of the numbers which I have obtained graphically from the published figures are only approximately correct.

Columns 7 and 9 give the records of observations made upon two small rings of very pure iron given by Colonel Dyer of the Elswick works to

Wilson, Proc. Roy. Soc., **62**, 1898; du Bois, Ann. d. Physik, **51**, 1894 (537); Taylor Jones, Ann. d. Physik, **54**, 1895 (641); Phil. Mag., **39**, 1895 (254); Stefan, Wiener Berichte, **81**, 1880 (89); Ewing, Roy. Soc. Trans.

TABLE III.

H.	B.											
	Norway Iron (F) Rings, 1 and 2.	Long Rod of Norway Iron. (R.)	American Ingot Iron.	Hopkinson's Annealed Wrought Iron. (Average.)	Lehmann's Swedish Iron Ring.	Rösler's Iron Ellipsoid.	Wilson's Ring of Pure Iron (No. 2).	Ewing's Soft Iron Wire.	Lydall and Pocklington's Ring of Pure Iron (No. 1).	Hopkinson's Ring.	Rowland's Norway Iron Ring.	Norway Iron (Q).
0.2	145	90	106	110	140	68	300	26	46	80	100	115
0.4	495	260	324	340	450	165	800	55	128	170	380	340
0.6	1260	570	688	740	1180	282	1400	100	467	330	1100	780
0.8	2850	1125	1325	1280	2050	410	2050	160	1020	550	2500	1750
1.0	4730	2150	2320	2400	3020	560	3400	230	2150	950	4500	3050
1.5	8200	4600	5150	4700	4700	1550	8000	500	6020	3650	6950	5450
2.0	9870	6600	7340	5900	6050	4350	10700	900	7720	5400	8650	7200
2.5	10850	8240	9050	6800	7200	6950	12000	2500	8920	6780	9900	8200
3.0	11560	9480	10220	7600	8300	8700	12800	5800	9850	7800	10800	9150
3.5	12010	10460	11150	8350	9150	9800	13400	8400	10600	8800	11450	10050
4.0	12310	11280	11900	9000	9700	10600	13800	10350	11300	9600	12020	10800
4.5	12550	11980	12450	9500	10150	11240	14150	11650	11850	10250	12500	11400
5.0	12760	12560	12850	9950	10650	11800	14360	12480	12350	10750	12070	11900
6.0	13060	13400	13500	10700	11400	13700	14700	13500	13200	11500	13700	12800
7.0	13300	13900	13960	11300	12050	13400	14950	14100	13900	12100	14100	13400
8.0	13510	14300	14350	11800	12550	13780	15100	14350	14400	12550	14400	13850
9.0	13700	14660	14600	12180	12900	13960	15250	14750	14800	12950	14680	14200
10.0	13870	14940	14830	12500	13280	14050	15320	14950	15050	13350	14950	14400

Sir Frederick Abel, who presented them to Dr. John Hopkinson. The tests upon the first ring by Messrs. Pocklington and Lydall seem to show that they did not anneal the iron; the remarkable measurements of Wilson upon the second ring were made after the iron had been softened. Norway Iron (R) was a long annealed rod about half an inch in diameter. This was tested in a solenoid. An analysis of Hopkinson's ring made by the Whitworths, showed manganese 0.143 per cent, phosphorus 0.271 per cent, sulphur 0.012 per cent, carbon 0.01 per cent and "slag" 0.436 per cent. The Elswick iron contained 0.1 per cent of manganese and 0.013 per cent of sulphur but no phosphorus and hardly a trace of carbon or other impurity. Norway Iron (Q) was an annealed ring cut from a bar of "pure iron" obtained in the Boston market.

My thanks are due to Professor John Trowbridge, who furnished me with the pure iron described above, and to the Trustees of the Bache Fund of the National Academy of Sciences who loaned me some of the apparatus used in the work.

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